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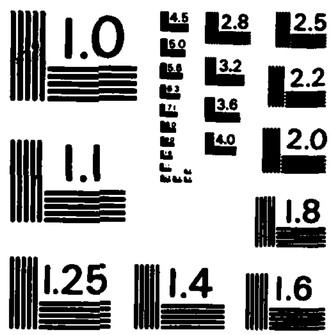

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GEOPHYSICAL SEEPAGE DETECTION STUDIES MILL CREEK DAM WALLA WALLA, WASHINGTON

by

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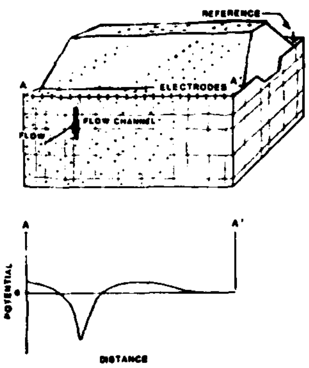

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

August 1984

Final Report

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A geophysical seepage detection study which used the self-potential (SP) method was conducted at Mill Creek Dam and Reservoir in Walla Walla, Washington. The reservoir has experienced excessive loss of stored water due to seepage since its first test filling in 1941. The seepage pattern was not altered by remedial measures attempted at various times from 1941 to 1979.

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20. ABSTRACT (Continued).

Following a recommendation of the August 1979 General Design Memorandum, a concrete cutoff wall with flanking grout curtains was constructed. The reservoir has not held appreciable amounts of water since completion of the cutoff wall, hence, to test the effectiveness of the new remedial measures, a test filling of the reservoir was scheduled during April and May 1984.

The objective of this investigation was to monitor SP values over two permanently installed electrode arrays as the reservoir filling progressed. Array 1 was installed from Station 18+00 to Station 41+50 along the elevation 1,225-foot contour on the upstream face of the dam, just downstream of the location of the cutoff wall. Array 2 ties into Array 1 at Station 32+00 and proceeds approximately perpendicular to Array 1 in the upstream direction beginning at Station 0+00 and commencing at Station 18+00. For each array, anomalous SP values, especially those which increase or decrease as a function of time, were flagged as possible indicators of seepage paths. A qualitative ranking scheme was developed to rank the relative importance of detected anomalous zones. The following conclusions were formed from analysis of the data.

a. Two SP anomalous zones located along Array 1 were rated highly significantly. These zones were located between Station 17+00 and Station 18+25 and between Station 29+25 and Station 31+75.

b. Two highly significant anomalous zones were interpreted along Array 2 between Station 3+25 and Station 3+75 and between Station 9+25 and Station 10+75.

c. Array 1 anomaly between Station 29+25 and Station 31+75 and Array 2 anomaly between Station 0+25 and Station 0+75 occur in the vicinity where the dam and the right abutment contact.

d. A poorly defined anomaly was interpreted on Array 1 between Station 35+00 and Station 38+00 and is the only anomalous zone between Station 32+00 and 41+50 on this array, hence, possible correlation of anomalous zones on Array 2 with this section of Array 1 is not well justified.

e. The highly significant anomaly between Station 17+00 and Station 18+25 of Array 1 apparently coincides with an area identified by District personnel as exhibiting anomalous piezometer response and as the area of the cutoff wall most likely to be deficient.

Preface

A geophysical seepage detection study at Mill Creek Dam, Walla Walla, Washington, was authorized by the U. S. Army Engineer District, Walla Walla, under IAO No. 86840021, dated 22 October 1983.

The permanent electrode self-potential (SP) array was partially installed during the period 9-10 November 1983 by Dr. Dwain K. Butler and Mr. Ronald E. Wahl of the Earthquake Engineering and Geophysics Division (EEGD) of the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES). Mr. Grady Williams of the Walla Walla District supervised the completion of the array installation and the acquisition of the SP data during April and May 1984. The data analysis phase of this study was performed by Dr. Butler with assistance from Messrs. Wahl and Michael K. Sharp under the general supervision of Dr. Arley G. Franklin, Chief, EEGD, and Dr. William F. Marcuson III, Chief, GL. This report was written by Dr. Butler.

COL Tilford C. Creel, CE, was Commander and Director of WES during the performance of this investigation and the preparation of this report. Mr. Fred R. Brown was Technical Director.

Contents

* Appendices B-E are not bound in this report. They are on file in the Earthquake Engineering and Geophysics Division, Geotechnical Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss. 39180.

GEOPHYSICAL SEEPAGE DETECTION STUDIES, MILL CREEK DAM, WALLA WALLA, WASHINGTON

Background

1. During the period 9-10 November 1983, personnel from the Earthquake Engineering and Geophysics Division, Geotechnical Laboratory, US Army Engineer Waterways Experiment Station (WES), partially installed a permanent self-potential (SP) measurement electrode array at Mill Creek Dam, Walla Walla, Washington. Also, Walla Walla District personnel were instructed on procedures for making the SP measurements. District personnel then completed installation of the electrode array and forwarded measurement data to WES, as acquired during an April-May 1984 test filling of the reservoir. This work was authorized and funded by Intra-Army Order No. E86840021, 22 October 1983, from Walla Walla District, Corps of Engineers.

2. Mill Creek Dam and Reservoir has experienced excessive loss of stored water due to seepage since its first test filling in 1941. The seepage pattern was not altered by remedial measures attempted at various times from 1941 to 1979. Following a recommendation of the August 1979 General Design Memorandum, a concrete cutoff wall with flanking grout curtains was constructed approximately along the upstream 1225-ft* elevation contour of the dam. The reservoir has not held appreciable amounts of water since completion of the cutoff wall (due both to seepage and purposefully not diverting water from Mill Creek into the reservoir).

3. The objective of the present study was to monitor SP values over the electrode array as a function of time before and during the April-May 1984 test filling. Anomalies in the SP values, particularly those which increase or decrease as a function of time, will be flagged as possible indicators of seepage paths. The SP method will not be discussed in detail in this brief report; however, the general strategy of geophysical methodology for seepage detection, mapping, and monitoring is covered in Appendix A.** Results from this study will be used in conjunction with known geology, construction history and details, and piezometer data in making the final seepage assessment and planning remedial measures.

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* To convert feet to metres, multiply by 0.3048.

** Appendix A is a brief paper prepared for a specialty session on geotechnical applications of the SP method at the 1984 International Meeting of the Society of Exploration Geophysicists.

Approach and Procedures

4. Two SP electrode arrays were installed by WES and Walla Walla District personnel as shown in Figure 1. Array 1 was installed from Station 18+00 to Station 41+50 along the elevation 1225 ft contour on the upstream face of the dam, slightly downstream of the location of the cutoff wall. Array 2 ties in to Array 1 at Station 32+00 and proceeds approximately perpendicular to Array 1 from 0+00 to 18+00 (separate stationing scheme from Array 1). Electrode spacing along both arrays is 50 ft. A reference electrode was located approximately 1200 ft east of Station 18+00 of Array 1 (upstream of dam).

5. The field procedure consisted of measuring potential differences (voltages) between the reference electrode and each of the Array 1 and 2 electrodes using a digital millivoltmeter. Since the SP arrays were to be monitored over a period of several months involving numerous sets of measurements, a "permanent" reference wire was installed with connection points for each electrode. A single SP measurement then could be taken by connecting the millivoltmeter clip leads to the reference wire and to the electrode. The "permanent" reference wire considerably expedited the measurement process, and a complete set of measurements could be acquired in approximately one hour.

6. The objective of the SP monitoring arrays is to detect anomalies, relative to a baseline set of readings, which can be attributed to seepage paths under the arrays. An anomaly which increases or decreases as a function of time (or reservoir water level) during the test filling is strongly indicative of changing seepage quantities.

7. Problems. Two major problems complicated the field data collection efforts and data processing and interpretation efforts: (1) vandalism and vehicle/foot traffic damage to the reference wire; (2) shifts in reference potential level for the arrays. Vandalism included theft of wire and pulling electrodes out of the ground. Traffic along the face of the dam resulted in breaks in the reference wire and shorts caused by breaks in the insulation. Changes in contact potential resulting from having to replace an electrode in the ground are not easily predictable. These were recurring problems throughout the efforts. There were shifts in the reference or "zero level" of the potential which affected large segments of the arrays or the complete

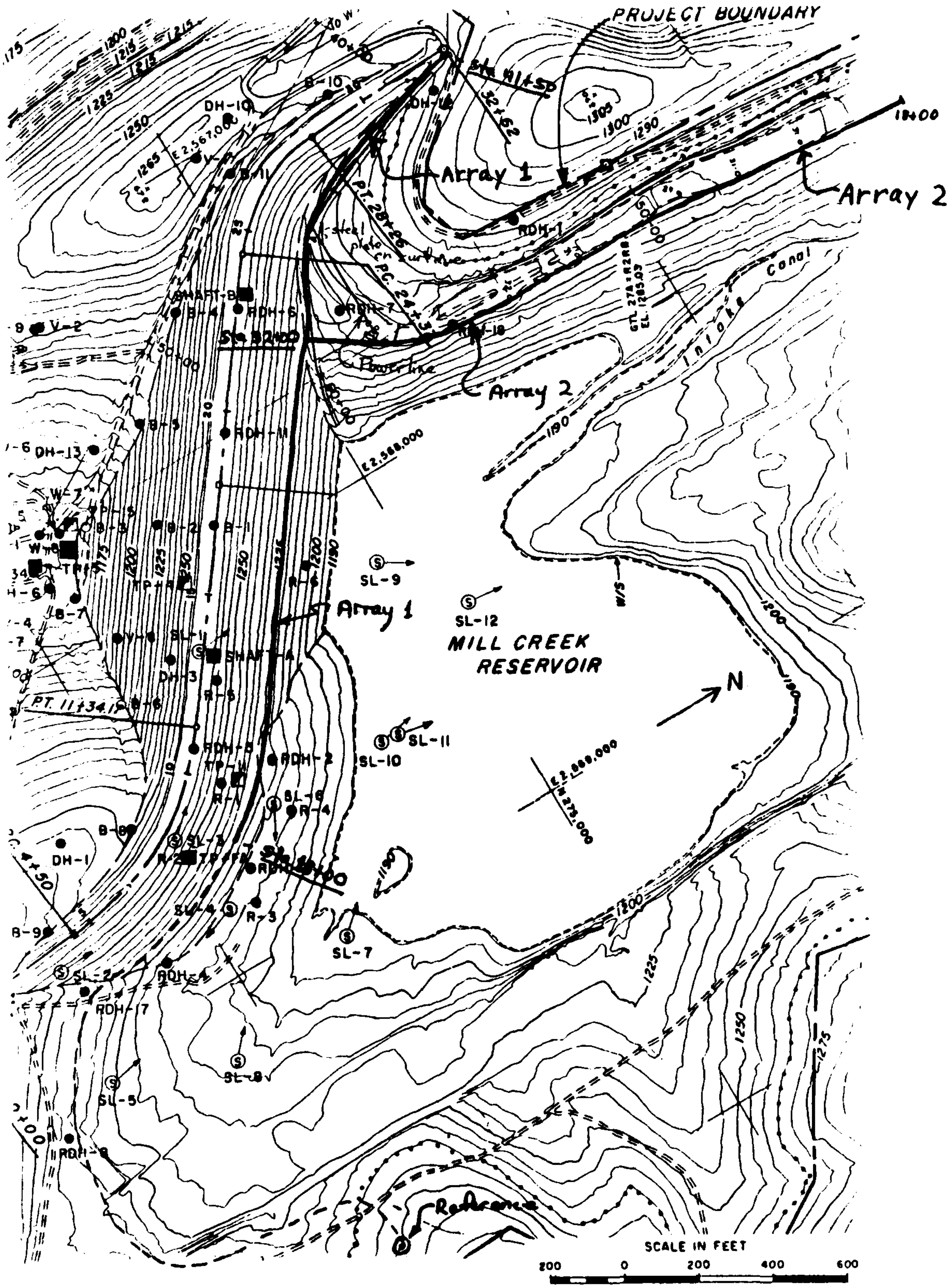

Figure 1. Mill Creek Dam site map showing locations of SP Arrays 1 and 2. (Drill hole designations and other symbols on site maps used in this report are explained in the August 1979 General Design Memorandum No. 5, Walla Walla District.)

arrays. Reference shifts could be caused by several conditions: (1) the potential at the reference electrode could change; (2) changing, relatively uniform flow or seepage under large segments of the arrays could cause apparent reference level shifts; (3) shorts in the reference wire could cause apparent reference level shifts for segments of the arrays (depending on where the short occurs). The complicating factors made it impossible to interpret the SP data in the usual straightforward manner.

Chronology

8. The following chronology includes only the major events in the SP monitoring project:

a. 9-10 Dec 1983--Arrays partially installed by WES personnel, initial sets of SP readings taken, instruction given to District personnel;

b. 1 Feb 1984--first complete set of SP readings on Array 1 by Walla Walla District personnel; due to theft of reference wire, District personnel were unable to find the original reference electrode, thus this set of readings utilized a new reference electrode;

c. 8 Feb 1984--first complete set of SP readings on both arrays by District personnel;

d. 14, 29 Feb and 9 March 1984--additional sets of SP readings;

e. 5 April 1984--beginning of test filling; pool elevation raised to 1191 ft; pool elevation during period 1 Feb to 4 April ~1187 ft;

f. 5, 6, 9, 11, 13, 18, 19, 20, April 1984--complete sets of SP readings; pool elevation 1221 ft during final set of SP readings.

Results

Field Data

9. Tables 1 and 2 are computer printouts of the Array 1 and 2 data sets respectively. Some of the data in the tables represent averages of morning and afternoon readings on the same day; otherwise, the data are unprocessed. Plots of the data are included in Appendices B-E. Appendices B and D are plots of SP values versus station for given days for Array 1 and 2 respectively; while Appendices C and E are plots of SP values versus time for individual electrodes for Array 1 and 2 respectively.

Array Averages and Observations

10. Figure 2 is a summary plot of unprocessed Array 1 data for 3 days (prior to the test filling). The data in Figure 2 illustrate two features of the results: (1) the data vary considerably along the length of the array; (2) for a given station, the SP values vary with time. The individual station values vary by as much as 100 millivolts. Examination of Figure 2 as well as the plots in Appendices B and D reveals that plots for a given day are generally parallel to plots for other days along the arrays, i.e., the average value for the arrays shifts (e.g., a reference shift). Figures 3 and 4 show array averages versus time. Since the array average versus time trend as well as the individual electrode versus time trends (Appendices C and E) are qualitatively similar, it seems that the predominant cause for time variations are reference level shifts which affect an entire array similarly. Thus the array averages seem to be good reference level indicators.

11. Examination of the plots in Figure 2 reveal 3 zones along the dam; these zones were also noted in the original SP data collected by WES personnel in December 1983. The zones are characterized by apparent changes in average value along the array; for example, the average value changes from approximately 500 mv for Zone 1 to 300 mv for Zone 2 to 50 mv for Zone 3. This same pattern of zones is observed for the array profiles during the test filling, and the array averages as well as the zonal averages generally decrease with time during the test filling. Several features are worth noting in Figure 2: (1) the large anomaly at Station 27+50 of Array 1 nearly coincides with the outlet conduit; (2) the Zone 1/Zone 2 boundary approximately coincides with the dam/abutment contact; (3) the Zone 2/Zone 3 boundary approximately coincides with the end of the grout curtain. Possible explanations for observations (2) and (3) above are that the Zone 1/Zone 2 boundary is due to a lateral change in material type and that the Zone 2/Zone 3 boundary is due to a lateral change in groundwater flow regimes caused by the presence of the cutoff wall and grout curtain.

Processed Data

12. It is clear that SP data variations along the arrays and SP data variations with time preclude an effective straightforward identification of anomalies. A type of processing is applied to the data which attempts to remove reference level shifts and isolate anomalies. If $V(I,J)$ represents an SP measurement at station J made on day I and $\overline{V(I,J)}$ represents the array

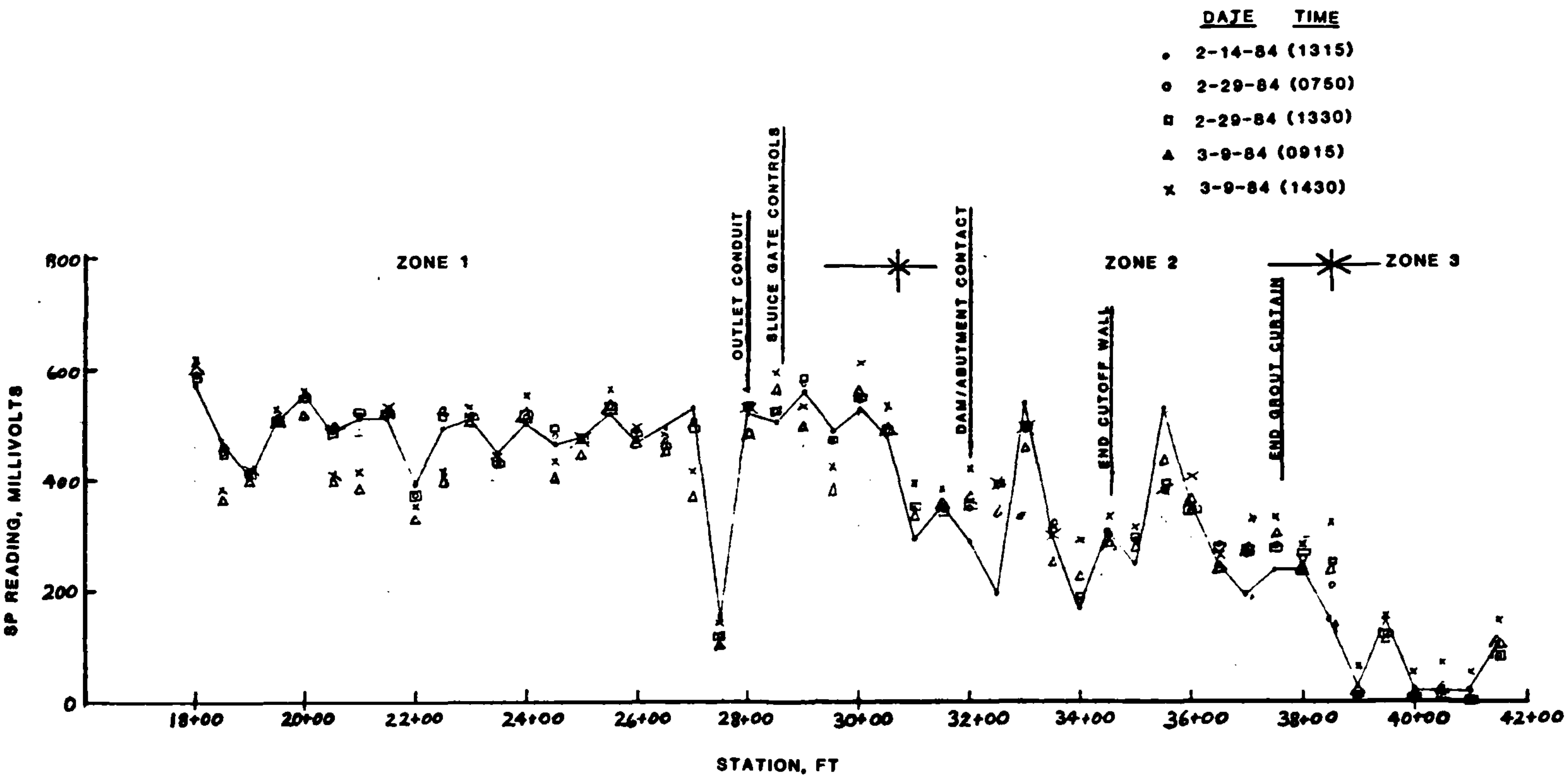

Figure 2. Unprocessed Array 1 SP Data (Pre-Test Fill) showing identification of three zones based on the data and location of selected features along the array. Pool elevation--1187 ft.

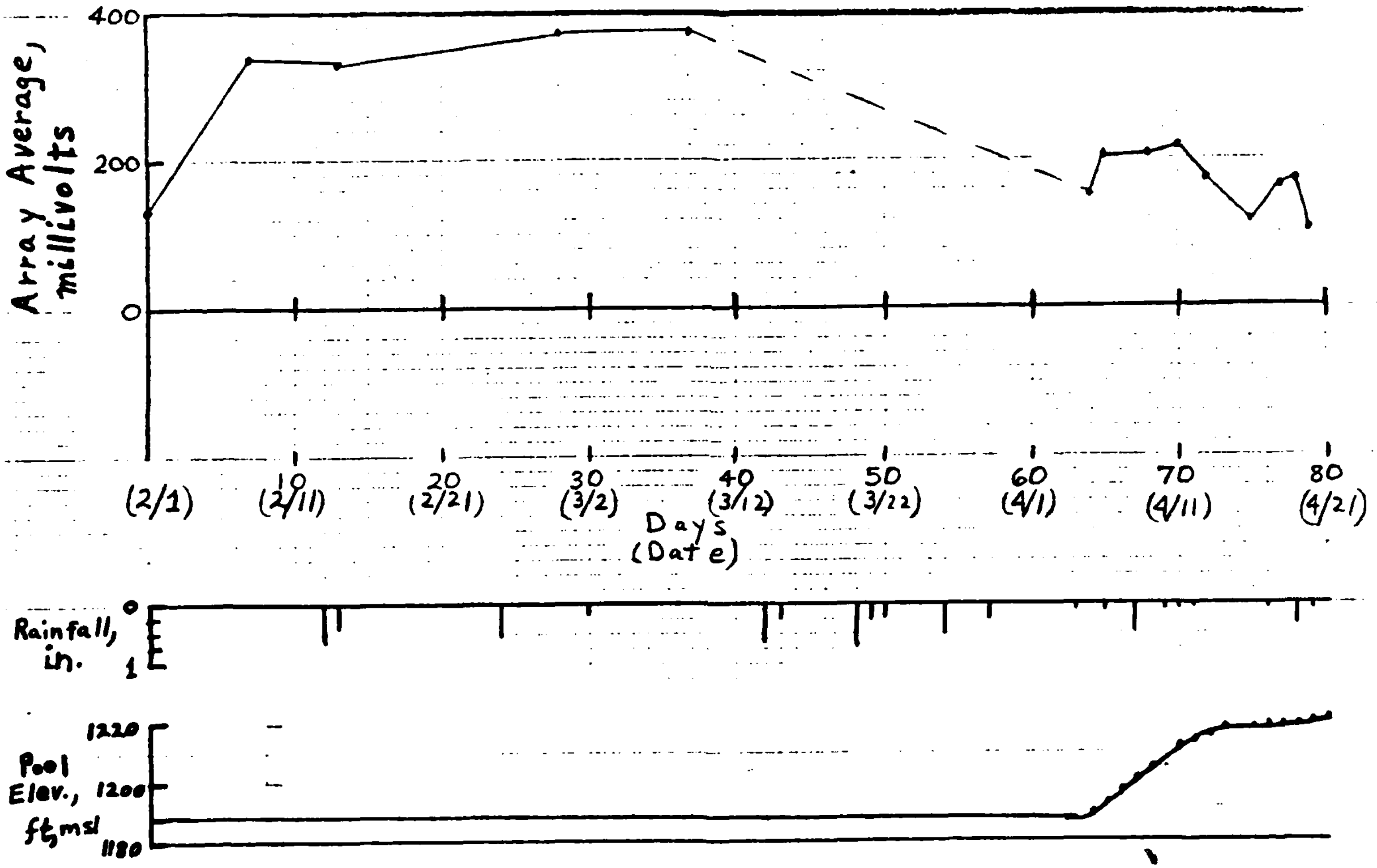

Figure 3. Array averages versus time for Array 1.

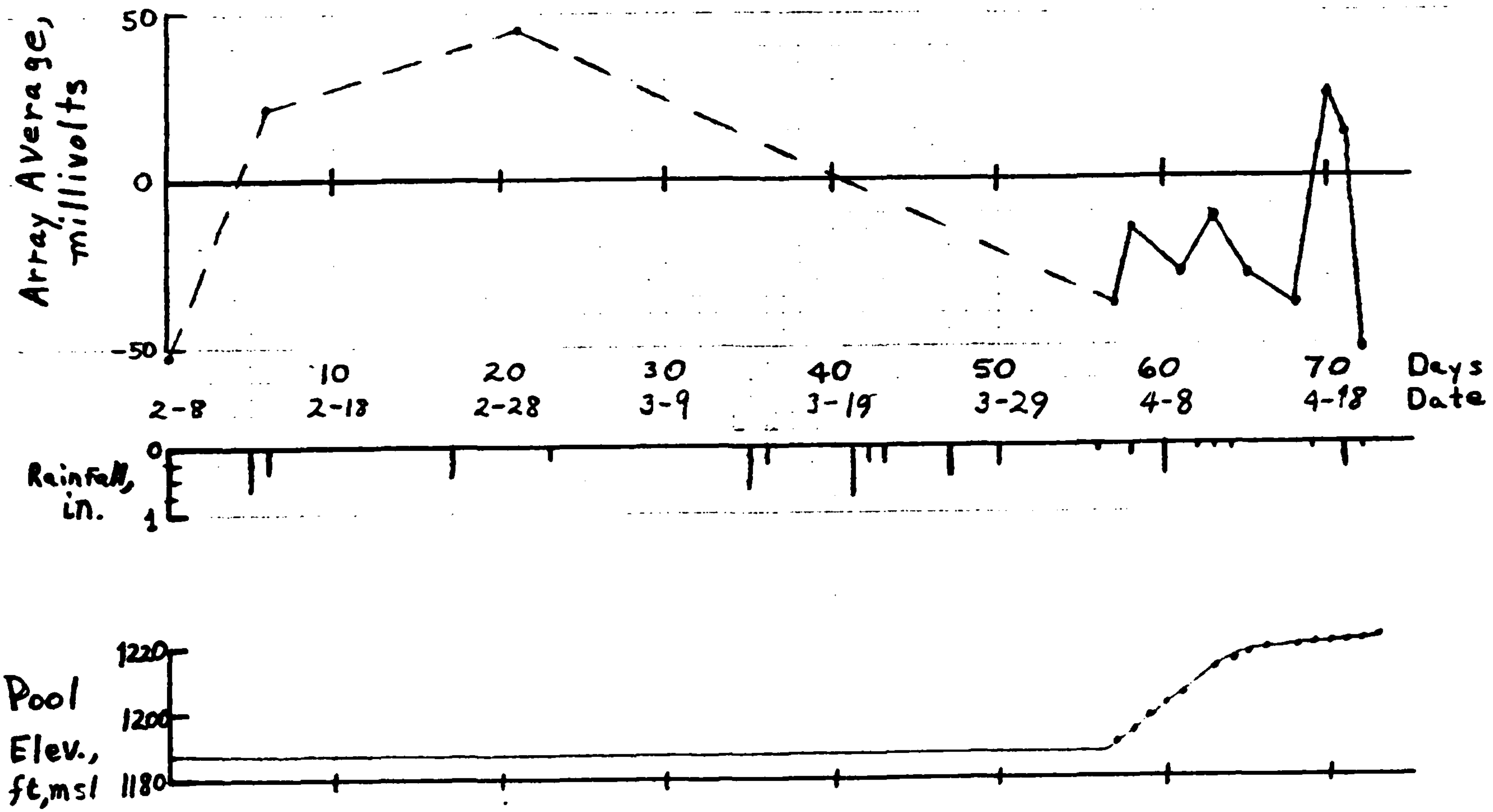

Figure 4. Array averages versus time for Array 2.

average for day I, then an array average difference is defined as

$$\Delta_{BI} = \overline{V(B,J)} - \overline{V(I,J)},$$

where $\overline{V(B,J)}$ refers to the array average for the day chosen to be the baseline or pre-fill reference set of SP array values. An SP anomaly profile for one of the arrays is then defined as

$$V_{BI}(J) = V(B,J) - [V(I,J) + \Delta_{BI}]$$

That is, the profile for day I is shifted by the difference in array averages (Δ_{BI}), and then the shifted profile is subtracted from the reference profile.

13. For Array 1, processed SP anomaly plots were generated using both the pre-test fill 9 March data and the 5 April (first day of test fill) as baseline profiles. Figures 5 and 6 contain summary plots of several Array 1 SP profiles referenced to 9 March and 5 April respectively. Figure 7 presents anomaly plots for several Array 2 profiles referenced to the 5 April profile.

14. For Array 1, a second type of processed anomaly plot was generated. Zone averages, for the three zones along the array, were computed for 5 April and 20 April, and an anomaly plot was produced using the zone averages instead of the array averages. Figure 8 is the zone average anomaly plot for Array 1.

Interpretation

15. In order to interpret the SP anomaly plots, a 100 millivolt threshold will be used for attaching significance to an anomaly. This procedure may be overly conservative, but at least spurious anomalies caused by time variations or variations in contact potential at individual electrodes will be eliminated. The 100 millivolt threshold is shown in Figures 5-8. Anomalous zones which exceed the threshold are indicated on the figures.

16. A qualitative significance ranking for the anomalous zones is adopted. For Array 1, the ranking scheme is as follows:

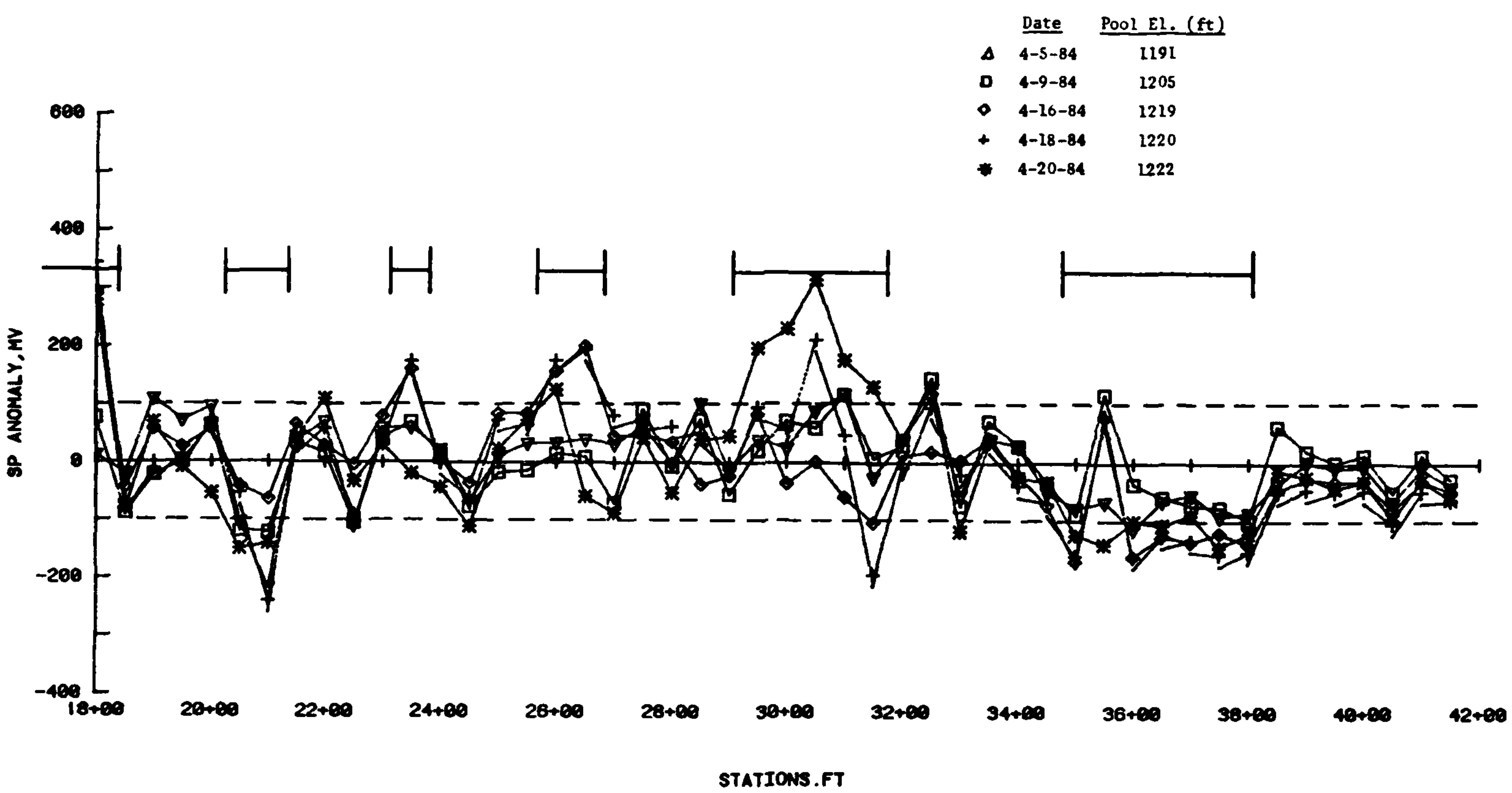

Figure 5. SP anomaly profiles for Array 1, referenced to the 3-9-84 data.

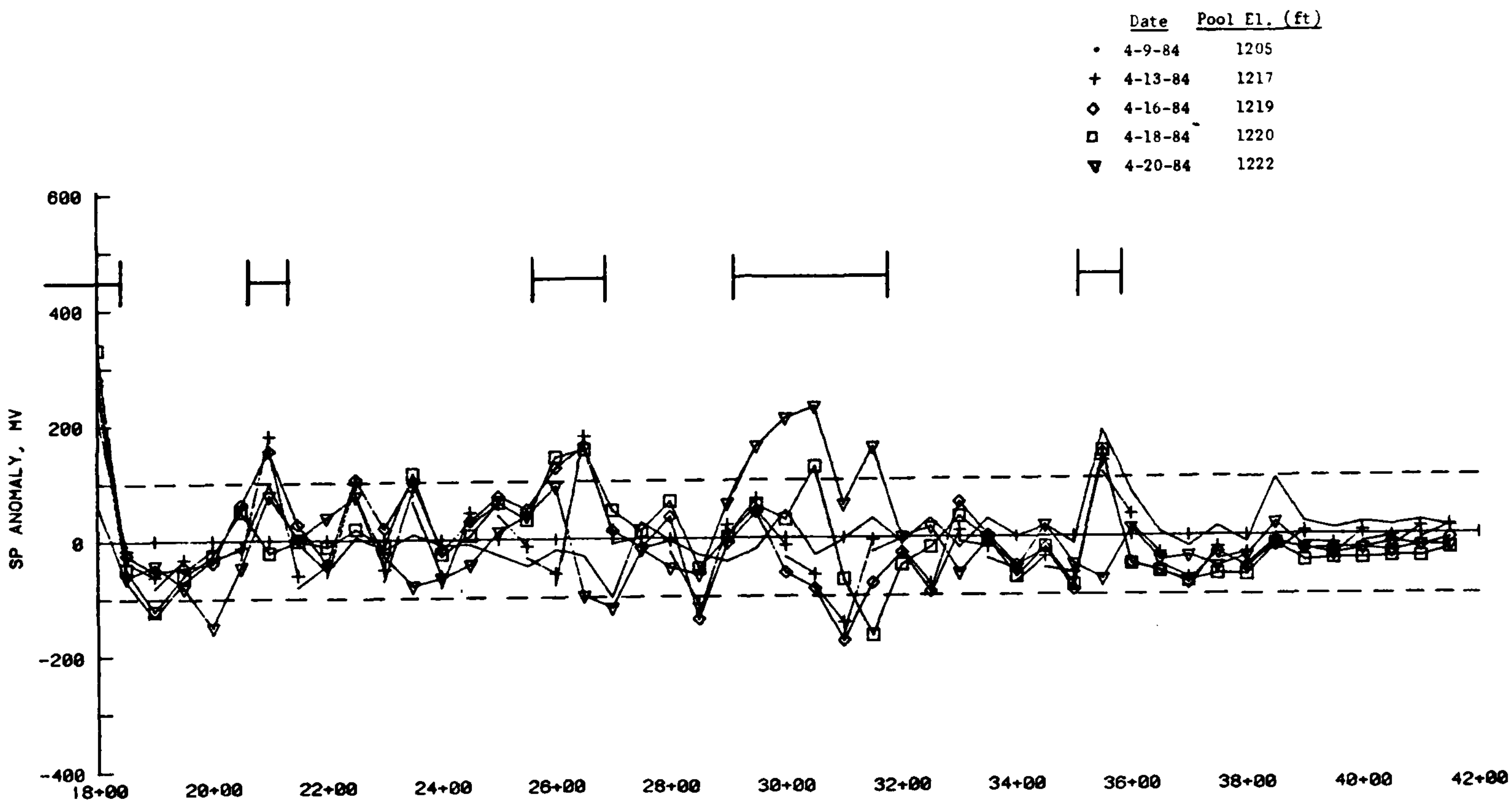

Figure 6. SP anomaly profiles for Array 1, referenced to the 4-5-84 data.

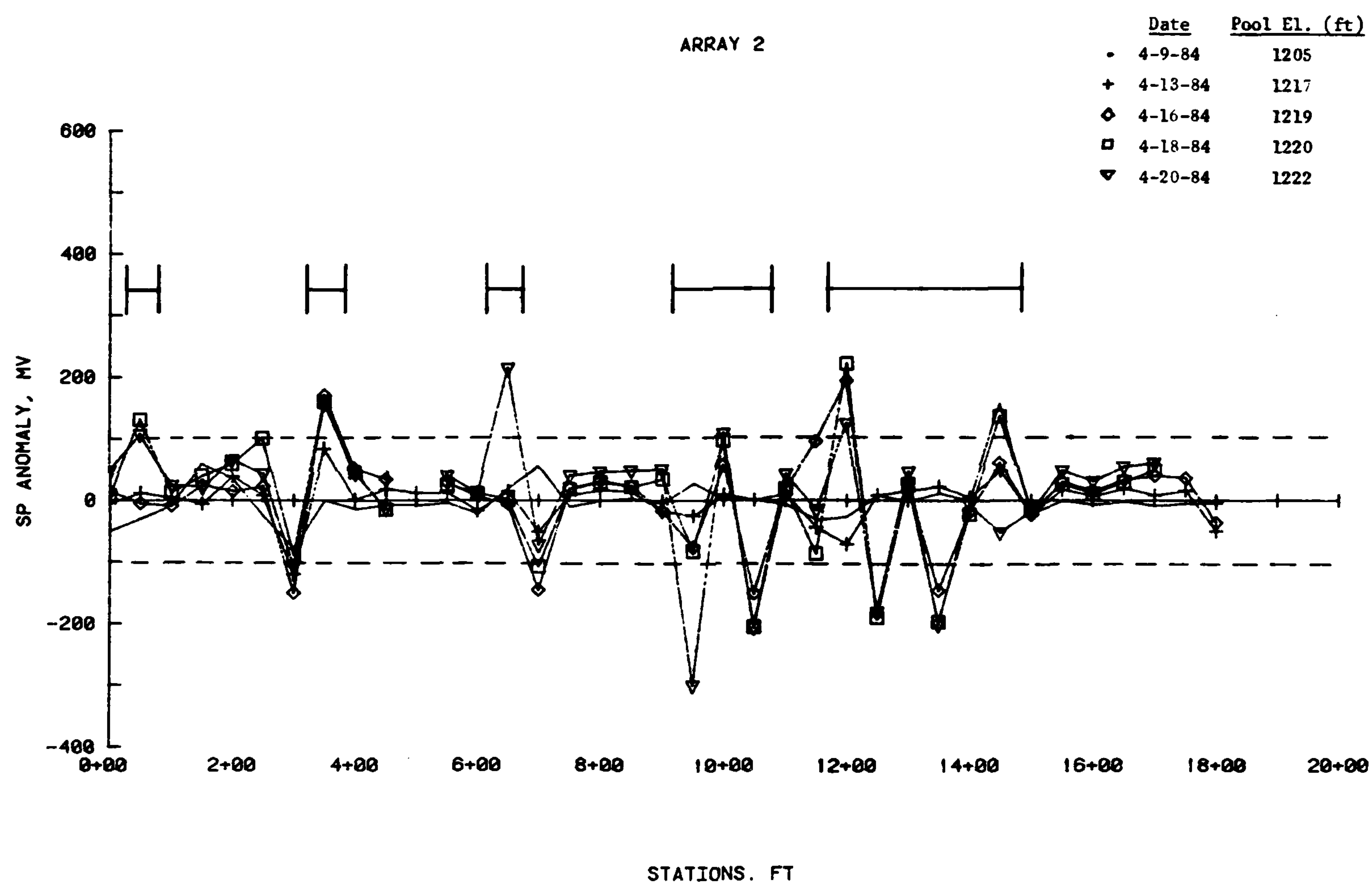

Figure ~. SP anomaly profiles for Array 2, referenced to the 4-5-84 data.

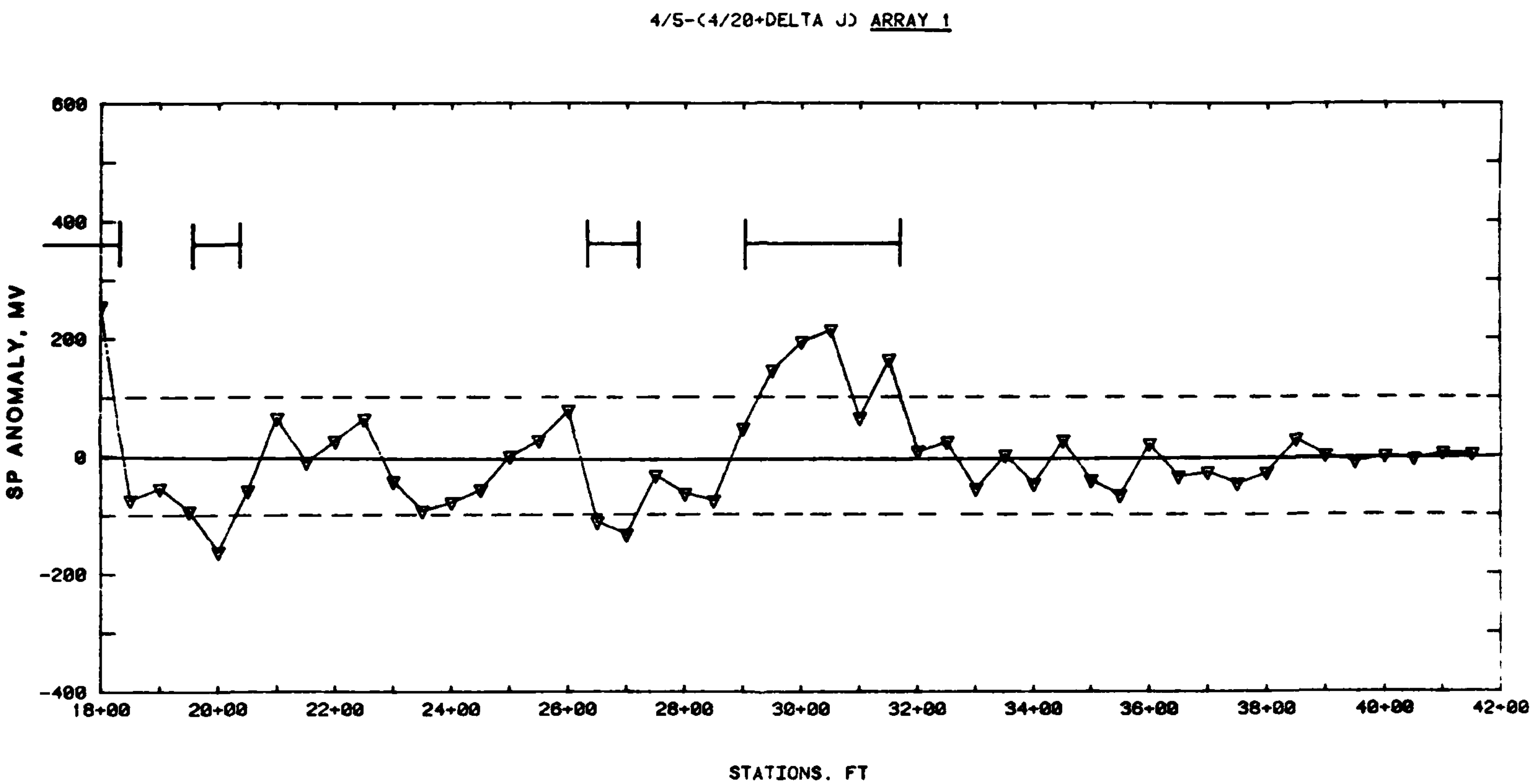

Figure 8. SP anomaly profile for 4-20-84 referenced to the 4-5-84 data using zonal averages.

Significance	Rank	Criteria	Anomaly Zones
Decreasing ↓	A	Anomaly zone is defined on all three anomaly plots and monotonically increases or decreases during pool raise	17+00--18+25
	B	Anomaly zone is defined on all three anomaly plots	29+25--31+75
	C	Anomaly zone is defined on two anomaly plots	19+75--20+25 20+25--21+25 25+75--26+75 35+25--35+75
	D	Anomaly zone is defined on only one anomaly plot	23+25--23+75 35+00--38+00

Similarly, the ranking scheme for Array 2 is:

Significance	Rank	Criteria	Anomaly Zones
Decreasing ↓	A	Anomaly well defined and monotonically increases or decreases during pool raise	3+25--3+75
	B	Anomaly "well" defined	00+25--00+75 2+75--3+75 11+25--14+75
	C	Anomaly "poorly" defined	6+25--6+75

These anomaly zones are shown as cross-hatched segments along the two arrays in Figure 9. The interpreted anomalies and associated significance ranking should be utilized in conjunction with known geology, construction history and details, and piezometer data in making the final seepage assessment.

Summary and Conclusions

17. The following facts summarize the work performed and documented in this report:

a. Two self-potential (SP) arrays were installed at Mill Creek Dam for monitoring seepage during a test filling of the reservoir;

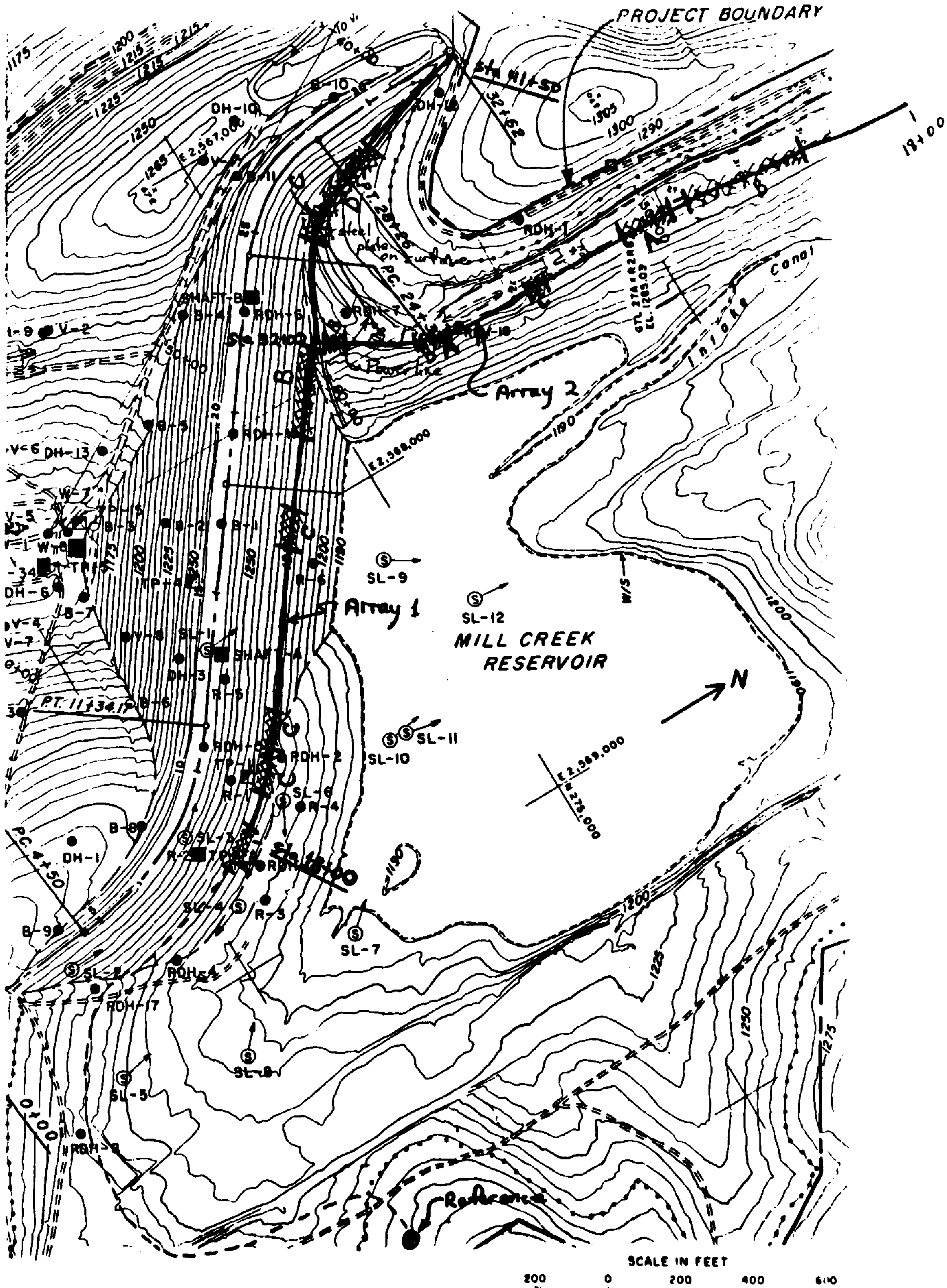

Figure 9. Interpreted SP anomalous zones. See text for explanation of significance ranking.

b. The field procedure involved installation of "permanent" electrode arrays; ideally all that should change during the monitoring would be induced seepage under the arrays during the test filling;

c. The effort was plagued by continuing acts of vandalism and damage to the arrays due to vehicular and foot traffic;

d. A data processing scheme was used to try to detect SP anomalies in the presence of reference level variations and other data variations caused by changing conditions of the arrays;

e. SP anomalous zones are indicated on a site map.

18. Conclusions are presented with reference to Figure 9. The field arrays were designed for a monitoring function during the test fill and not a mapping function, hence it is not possible to predict seepage directions unambiguously from the interpreted SP anomalous zones in Figure 9. The key conclusions are as follows:

a. Only two highly significant SP anomalies are interpreted along Array 1, 17+00 to 18+25 and 29+25 to 31+75;

b. Two highly significant anomalies are interpreted along Array 2, 3+25 to 3+75 and 9+25 to 10+75;

c. Array 1 anomaly 29+25 to 31+75 and Array 2 anomaly 00+25 to 00+75 occur in the vicinity of the dam/right abutment contact;

d. The anomaly indicated from 35+00 to 38+00 on Array 1 is poorly defined and is the only anomalous zone from 32+00 to 41+50 of Array 1, hence possible correlation of anomalous zones on Array 2 with this section of Array 1 is not well justified;

e. The anomaly from 17+00 to 18+25 of Array 1 apparently coincides with an area identified by District personnel as exhibiting anomalous piezometer response and as the most likely area of a "deficiency" in the cutoff wall.

Table 1

SP Field Data for Array 1

Date of SP Reading (Month/Day)

Stations (Ft)	2/1	2/8	2/14	2/29	3/9	4/5	4/6	4/9	4/11	4/13	4/16	4/18	4/19	4/20
18+00	80	440	539	589	608	376	366	365	425	154	61	57	61	62
18+50	192	416	428	451	377	177	209	300	240	213	160	238	322	192
19+00	149	376	366	416	400	78	109	264	204	160	99	213	245	73
19+50	240	466	467	509	518	227	260	352	378	279	240	300	362	261
20+00	275	487	516	547	534	219	247	305	275	254	225	258	377	322
20+50	209	431	452	484	401	285	345	354	362	317	190	248	353	284
21+00	218	448	472	519	390	397	342	354	316	237	210	432	372	273
21+50	287	496	480	521	522	264	341	323	356	345	204	279	298	214
22+00	162	376	357	373	340	50	141	158	161	113	59	75	80	-36
22+50	269	483	461	519	404	293	338	342	355	215	155	287	330	170
23+00	273	482	473	515	510	239	304	310	330	311	187	264	302	222
23+50	212	412	412	433	433	153	222	198	169	80	20	52	212	186
24+00	254	473	462	515	536	293	353	357	395	376	279	331	388	312
24+50	241	469	428	484	417	264	311	328	358	238	200	271	342	261
25+00	233	440	442	473	461	230	285	312	306	189	123	180	293	170
25+50	285	501	481	533	549	296	347	397	412	329	212	276	360	209
26+00	243	452	439	486	479	225	280	290	308	305	69	96	222	87
26+50	248	432	450	462	467	207	273	292	195	49	13	65	277	259
27+00	296	497	466	501	388	136	255	292	228	144	89	100	233	209
27+50	-68	115	114	119	118	-165	-142	-139	-133	-148	-182	-165	-134	-192
28+00	280	493	482	532	497	279	334	330	364	303	209	228	380	283
28+50	294	518	462	523	570	255	329	330	360	390	363	320	307	271
29+00	307	512	510	501	514	300	305	403	411	305	284	319	345	201
29+50	217	458	445	471	396	136	224	209	183	80	59	93	101	-70
30+00	308	488	487	547	504	339	391	346	414	373	367	321	220	85
30+50	255	459	442	480	508	190	273	282	307	282	253	88	36	-76
31+00	115	336	248	351	364	24	60	80	191	191	170	109	22	-80
31+50	141	313	317	340	366	171	201	192	223	195	217	354	111	-32
32+00	101	310	246	354	395	136	100	199	105	157	129	196	120	88
32+50	111	283	146	391	360	34	172	56	193	133	96	65	22	-30
33+00	242	384	497	496	477	313	383	306	414	322	220	291	322	329
33+50	82	316	270	315	275	13	86	36	76	51	-22	31	5	-20
34+00	-55	140	139	184	261	11	94	65	92	89	28	93	35	19
34+50	49	231	287	295	300	140	219	176	194	195	120	171	103	74
35+00	142	324	239	295	297	154	230	221	262	237	214	251	193	155
35+50	260	506	501	388	460	306	364	176	194	195	129	171	103	333
36+00	196	395	338	344	394	287	262	264	254	270	302	349	315	227
36+50	117	315	207	282	345	190	231	238	243	240	218	265	247	185
37+00	28	250	154	284	303	137	201	210	223	230	186	229	166	125
37+50	-86	224	209	280	321	192	245	231	254	233	100	272	245	199
38+00	130	346	202	264	261	125	107	192	207	176	148	207	172	114
38+50	28	202	107	231	275	89	139	45	120	110	60	118	60	21
39+00	-220	-38	13	9	39	-182	-143	-149	-130	-167	-180	-123	-141	-205
39+50	-130	90	113	126	130	-75	-28	-30	-4	-38	-84	-20	-34	-87
40+00	-228	-40	-15	6	33	-182	-146	-140	-138	-168	-190	-127	-135	-204
40+50	-229	-39	-16	9	46	-109	-67	-70	-50	-85	-120	-57	-77	-126
41+00	-231	-42	-19	5	32	-100	-144	-140	-140	-172	-191	-127	-145	-207
41+50	-120	-215	72	83	127	-54	-10	-12	-15	-49	-79	-16	-14	-79

Table 2

SP Field Data for Array 2

Date of SP Reading (Month/Day)

Stations (Ft)	2/8	2/14	2/29	4/5	4/6	4/9	4/11	4/13	4/16	4/18	4/19	4/20
0+00	310	246	354	143	194	202	183	157	127	197	117	80
0+50	315	328	340	174	220	213	195	171	177	105	65	52
1+00	223	239	249	89	116	106	115	94	96	130	102	50
1+50	87	138	148	39	53	-11	56	54	13	61	65	3
2+00	4	86	119	51	28	25	26	21	34	54	1	-30
2+50	12	59	45	-144	-120	-110	-107	-143	-169	-183	-133	-202
3+00	225	263	288	142	165	229	273	271	290	292	263	234
3+50	66	175	94	121	165	130	105	46	-52	23	2	-52
4+00	-185	-69	-33	-78	-58	-55	-45	-71	-132	-62	-72	-137
4+50	-999	-999	-999	-109	-85	-93	-87	-118	-145	-32	-51	-111
5+00	-191	-81	-80	-125	-102	-108	-100	-128	-999	-999	-999	-999
5+50	-194	-115	-50	-159	-136	-146	-134	-162	-189	-122	-136	-214
6+00	-49	64	80	3	40	34	63	29	-5	53	30	-23
6+50	9	181	140	203	271	192	218	197	207	264	186	-27
7+00	-100	-34	87	92	127	45	113	152	235	261	161	149
7+50	-216	-135	-82	-175	-149	-156	-148	-175	-197	-132	-150	-231
8+00	-218	-139	-86	-176	-158	-167	-150	-184	-210	-144	-160	-238
8+50	-70	-134	-84	-175	-155	-170	-154	-180	-200	-135	-150	-239
9+00	-92	18	85	-28	11	-14	20	-1	-13	-1	-15	-94
9+50	15	80	-999	-71	-40	-90	-48	-37	3	73	208	214
10+00	127	45	-999	65	63	71	71	65	6	30	22	-59
10+50	-146	-40	1	-99	-69	-90	-73	-90	50	160	144	92
11+00	-190	-89	-39	-142	-124	-126	-121	-143	-163	-99	-116	-200
11+50	75	90	101	142	171	183	197	195	44	290	280	143
12+00	5	177	0	115	115	150	189	195	-82	-46	-25	-25
12+50	-130	-999	64	-45	-30	-44	-29	-45	136	207	180	121
13+00	-217	-144	-94	-176	-159	-166	-157	-183	-207	-141	-156	-238
13+50	-208	-47	-17	-116	-106	-119	-107	-130	20	143	144	70
14+00	-220	-162	-109	-171	-152	-161	-145	-167	-155	-87	-99	-179
14+50	75	144	200	86	136	-63	39	46	23	11	154	123
15+00	-214	-132	-61	-62	-33	-32	-21	-31	-41	14	1	-60
15+50	-210	-143	-89	-102	-166	-172	-166	-190	-214	-146	-163	-245
16+00	-60	-15	-9	-122	-103	-106	-94	-120	-139	-71	-90	-168
16+50	-198	-91	-55	-165	-150	-154	-149	-175	-201	-133	-145	-235
17+00	-27	60	31	-2	10	16	17	-1	-44	10	-2	-78
17+50	-80	52	20	-155	-141	-141	-130	-162	-193	-999	-999	-999
18+00	-220	-146	-195	-170	-156	-157	-150	-111	-136	-999	-999	-999

Appendix A: Geophysical Methods for Seepage Detection, Mapping, and Monitoring*

by

Dwain K. Butler

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*This Appendix is a paper submitted for presentation at the 1984 International Meeting of the Society of Exploration Geophysicists, Atlanta.

GEOPHYSICAL METHODS FOR SEEPAGE DETECTION, MAPPING, AND MONITORING

Summary

Seepage occurs through, under and around dams, levees and other water retention structures. When seepage rates exceed the capacity of drain systems or seepage occurs in an unexpected area, the integrity of the dam or levee may be threatened. Geophysical survey programs are now being successfully used to detect, map and monitor seepage paths. This report reviews the philosophy and methodology for geophysical studies for this purpose. Among the presently available geophysical methods, the self potential method stands out as an extremely cost effective and versatile tool for seepage studies. A brief case history illustrates the use of complementary surveys along a selected profile line at a dam to (1) locate and delineate a possible path for seepage and then to (2) detect an anomaly at that location attributable to seepage and correlatable to reservoir level.

Introduction

Earth dams are expected to seep, and dam designs include drain systems to collect and discharge seepage water into the downstream channel. Sometimes seepage occurs in an unplanned manner, however, exceeding the capacity of the drain system or along a path not considered in the seepage design. The unplanned and excessive seepage may be just unsightly or it may threaten the integrity of the dam. For either case, there is great need for a methodology to detect and map seepage paths.

Geophysical methods applied to seepage problems generally attempt to detect and map (1) an anomaly due to the geological condition that provides a seepage path, (2) an anomaly due to the relatively high water content in soils or rock along the seepage path, or (3) an anomaly due to the seepage itself (or some combination of these). In the first case, the path will be an anomalous condition in the dam, the foundation, or the abutments of the dam such as a fracture zone or solution channel. Although it is possible to have conditions such that seepage can occur over a broad zonal region, in most cases seepage occurs initially along a localized, linear trending flow path

which must cross the axis of the dam. In the third case, the seeping or streaming water must generate a detectable anomaly.

The three functions in the title of this paper refer to the strategy, scope and objectives of the geophysical field program. Detection of seepage or a seepage path refers to the location of a geophysical anomaly along a survey line which is interpreted to be due to crossing a path along which seepage may or may not be currently occurring. Of course mapping implies that the interpreted seepage path is detected on multiple survey lines. Depending on the type and extent of the geophysical program, the seepage path may just be mapped in plan or estimates of the size and depth of the seepage path may also be obtained. The monitoring function implies that the geophysical surveys are conducted along the same survey lines periodically in an attempt to detect and map anomalies which reflect changes in the seepage quantities and rates. Seepage monitoring surveys are valuable, for example, during periods when there are significant increases or decreases in reservoir pool level. The results of monitoring surveys can generally be interpreted more unambiguously than one-time surveys since anomalies are defined relative to preceding survey results.

Geophysical Methodology

The geophysical methods used in seepage studies are familiar: electrical resistivity sounding and profiling; self potential (SP); seismic refraction. Various types of resistivity profiling (including terrain EM surveys) and SP surveys are most generally applicable to seepage detection and mapping. Resistivity sounding and seismic refraction surveys are used primarily in a supporting role in seepage studies.

Various types of standard horizontal resistivity profiling surveys are used to detect and map potential seepage paths. The sense of the anomaly will vary depending on the nature of the path and whether or not seepage is occurring along the path. Fracture zones will generally produce low resistivity anomalies due to serving as an active seepage conduit or to the presence of clays and other weathering products. The resistivity anomalies due to solution features can be negative or positive; water- or clay-filled features will produce negative anomalies, while air-filled features will produce positive anomalies. If multiple electrode spacings are used along a profile line, depth ranges can be specified for features causing the anomalies, but generally the objective of horizontal resistivity profiling is to map anomalies in plan.

A modified pole-dipole surveying technique can be used for locating anomalies in three-dimensions and for estimating sizes of features producing the anomalies. The modified pole-dipole technique is actually a combined sounding-profiling procedure. The technique has been used quite successfully in site investigations in karst regions but is extremely labor intensive.

The SP method measures natural electrical potential field differences at the surface of the earth. Anomalies in the electrical field can be generated by conductive ore deposits or the flow of heat or fluids in the subsurface. The SP method has been used for at least fifty years in the USSR for geotechnical applications, such as seepage analysis and the study of landslide processes; and, likewise, the method has been used in the U.S. and Canada for at least fifty years for detecting and delineating conductive ore deposits. Use of SP surveys for geotechnical applications in this country is more recent and may be due to the appearance of a number of papers by Russian authors in English language technical journals during the period 1968-1972.

SP surveys for geotechnical applications are typically fixed reference point surveys, where each measurement point along a survey line or grid is relative to a reference potential which is generally the same for the complete survey. The reference electrode is generally located as far from suspected seepage zones as possible and in an area which is "quiet" electrically. There is some disagreement on the validity of metal electrode surveys; but for mapping and monitoring surveys, when the metal electrodes can be emplaced prior to initiation of the survey, the electrodes can reach electrochemical equilibrium and many of the arguments against metal electrodes are obviated. Thus, other than metal electrodes and reference wire, a digital readout millivoltmeter with 100 megohm or greater input impedance is all that is needed for an SP survey. Seepage paths are generally indicated by negative anomalies relative to the reference potential or to a no-seepage condition baseline value.

Thus the geophysical techniques used for seepage studies are familiar and not difficult to conduct. The complementary survey program must be planned, however, utilizing knowledge of the surface geometry of the dam and associated structures, the design and construction details of the dam, and the geology of the foundation and abutments to the maximum extent possible. Also the geophysical surveys must be considered an integral part of the overall seepage analysis by both the geophysicist and the project engineer. The survey lines

should be keyed to the existing or planned piezometer network. Borehole logs near resistivity sounding locations, seismic refraction lines, or horizontal resistivity profile lines should be used to constrain the interpretation.

Case History

A complementary geophysical survey program was conducted at a dam in Missouri in support of a comprehensive seepage analysis of the dam. The geophysical surveys were planned to investigate two specific areas of concern: (a) in the downstream left abutment areas above possible seepage paths; and (b) in the floodplain along the downstream toe of the dam to investigate an area where a piezometer boring encountered rock at 70 ft, compared to an average top of rock depth of 30 ft. This brief case history will concentrate on selected aspects of the efforts to detect and map the seepage paths (item a).

Figure 1 illustrates a portion of the dam and left abutment, showing a zone where seepage emerges during high reservoir levels. Rock below the floodplain and abutments is a dolomitic limestone which is cherty, intensely fractured, and highly weathered, particularly in the abutments. The top of the limestone is pinnacled, and air-, water-, and clay-filled cavities exist below the rock surface. Top of rock is typically about 50 ft below the surface of the smaller of the two left abutment ridges.

Geophysical surveys were conducted along both the base and crest of the left abutment ridge as shown in Figure 1. Results of two types of surveys along the crest of the ridge are shown in Figures 2 and 3. The pole-dipole survey results are interpreted to identify low (L) and high (H) resistivity anomalous zones beneath the profile line (Figure 2). The cluster of high and low anomalies at the water table below the 60 to 65 ft profile position in Figure 2 is particularly significant. A possible interpretation of the anomaly cluster is a solution feature which is partially air-filled (H) and partially water- and/or clay-filled (L). A verification of the interpretation shown in Figure 2 is provided by a clay-filled cavity intercepted in boring G-23, coinciding with the boundary of a low resistivity anomaly.

SP array 2A, shown in Figure 1, was monitored as a function of time during both high and low reservoir levels. The results of this series of surveys are shown in Figure 3. The low pool level surveys are very repeatable, mainly positive, and show only small variation about a mean value of ~25 mv. The high pool level surveys are less repeatable, show considerably greater

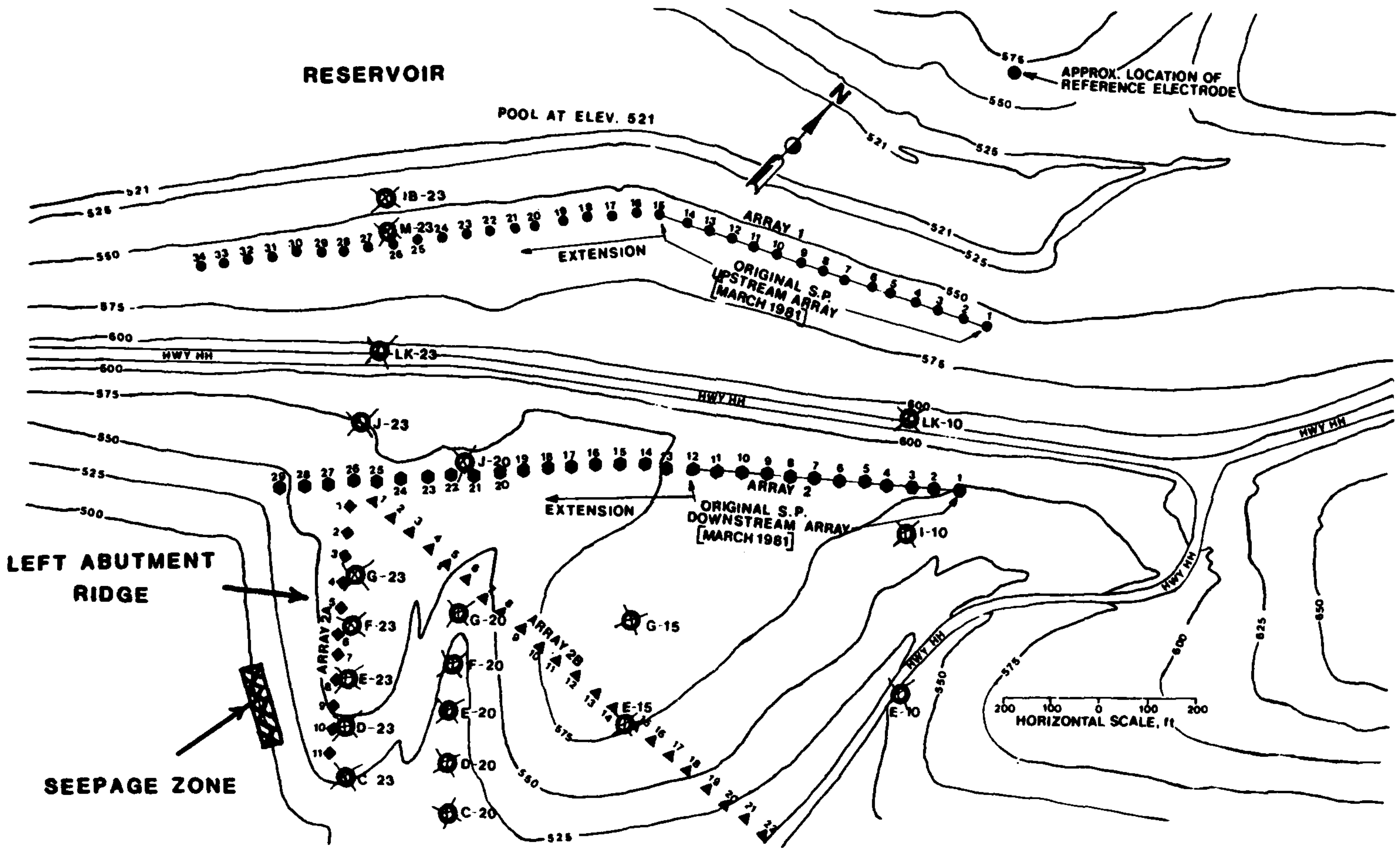

Figure A1. Site map showing seepage zone and the SP array installed to map and monitor seepage paths; Figures A2 And A3 present results of surveys conducted along the smaller of the two left abutment ridges.

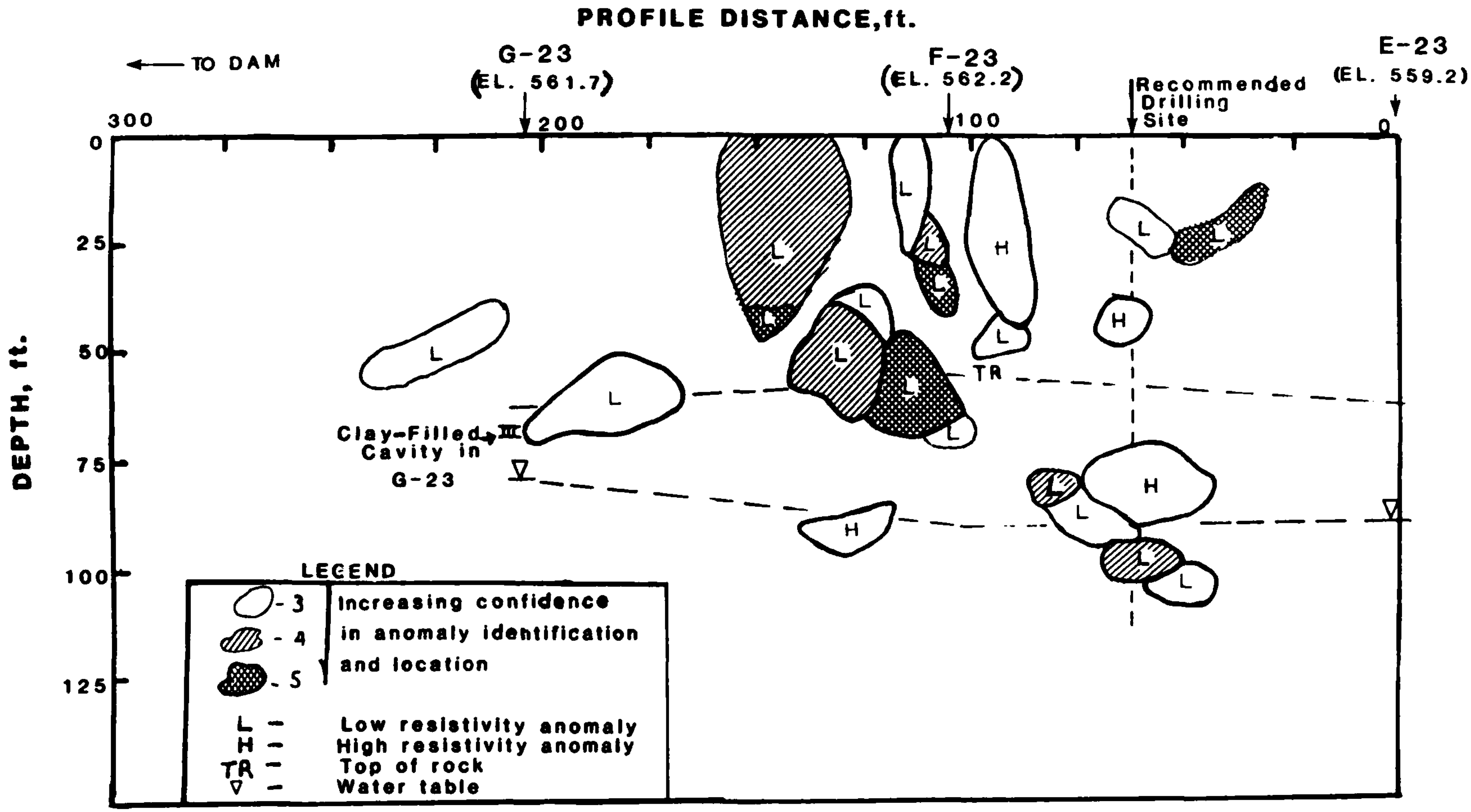

Figure A2. Interpreted results of pole-dipole resistivity survey along the left abutment ridge.

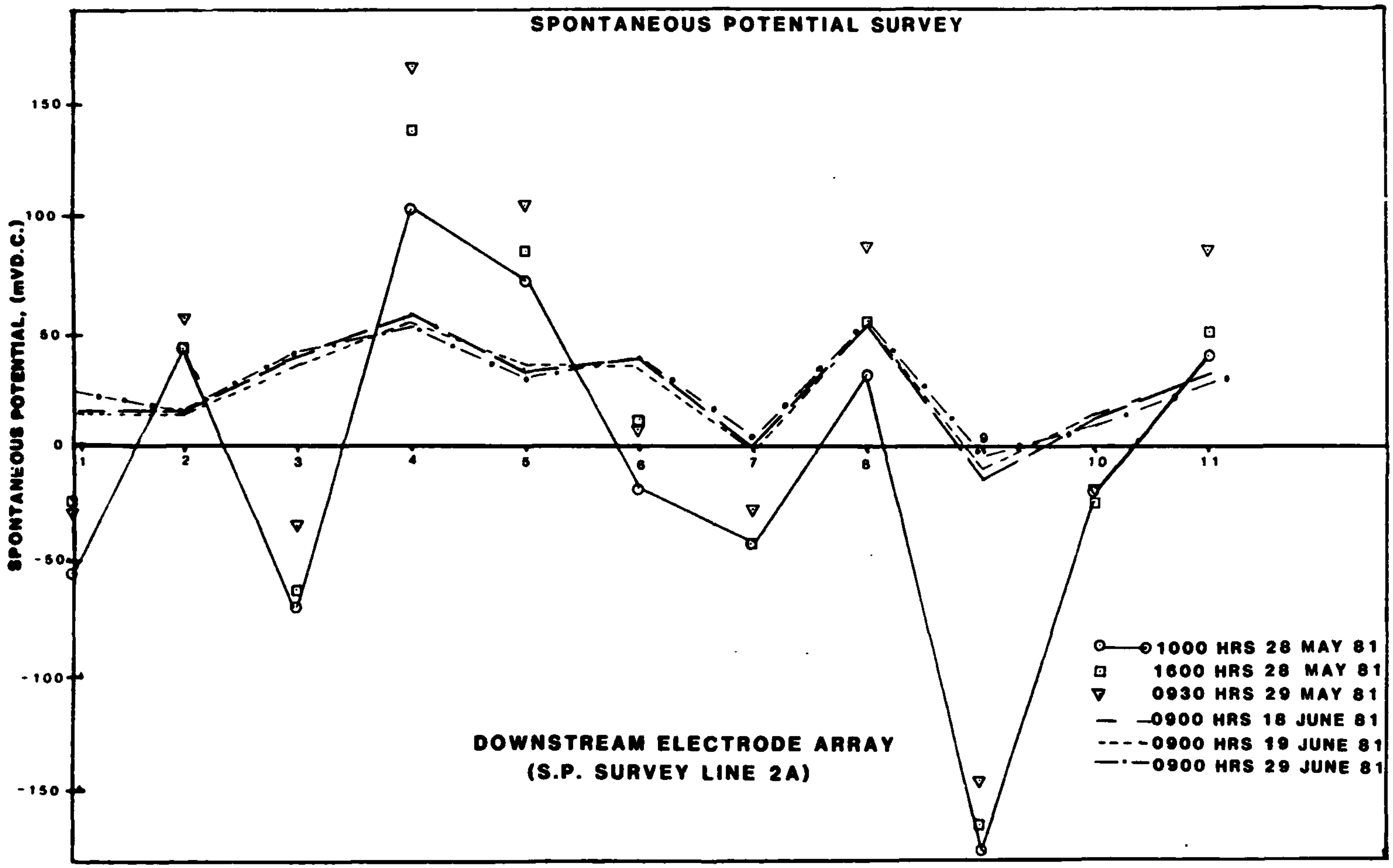

Figure A3. Results of SP survey along the left abutment during low (18-19 June 1981) and high (28-29 May 1981) reservoir levels.

variability, and a substantial portion of the survey line has negative SP values or is negative relative to the low pool level baseline. The broad SP anomaly centered at electrodes 5 and 6 coincides in location with the resistivity anomaly cluster discussed previously, and suggests that the interpreted air-filled portion of the cavity system may now be an active seepage path. The large amplitude SP anomaly at electrode 9 is beyond the extent of the pole-dipole survey line.

The results of all the geophysical surveys conducted at the dam site allowed patterns and trends to emerge in terms of probable seepage paths, as shown in Figure 4, and site geology. These trends are consistent with data from boring logs and water level data from an extensive piezometer network. However, due to the extremely complex spatial and temporal variations of piezometer data commonly associated with seepage through a carbonate rock with extensive solution features, it is doubtful in general if boring and piezometer data alone could ever provide a seepage analysis such as shown in Figure 4.

Conclusions

Geophysical survey programs can contribute significantly to seepage analyses. Ideally, complementary survey types should be conducted and tied to existing borehole data where possible. However, considerable experience, such as the brief base history presented in this paper, has shown that self potential (SP) surveys can be utilized in a stand alone manner for seepage mapping and monitoring. Seepage paths are indicated by negative anomalies relative to a reference electrode placed in a "stable" area away from the seepage zones. The negative anomalies can also be relative to a no-seepage condition baseline SP survey. SP surveys are a very cost effective way of delineating seepage paths in plan. The surveys can be planned and the data interpreted by geophysicists, but the data can be collected by project engineers or technicians from in-place arrays as a function of time.

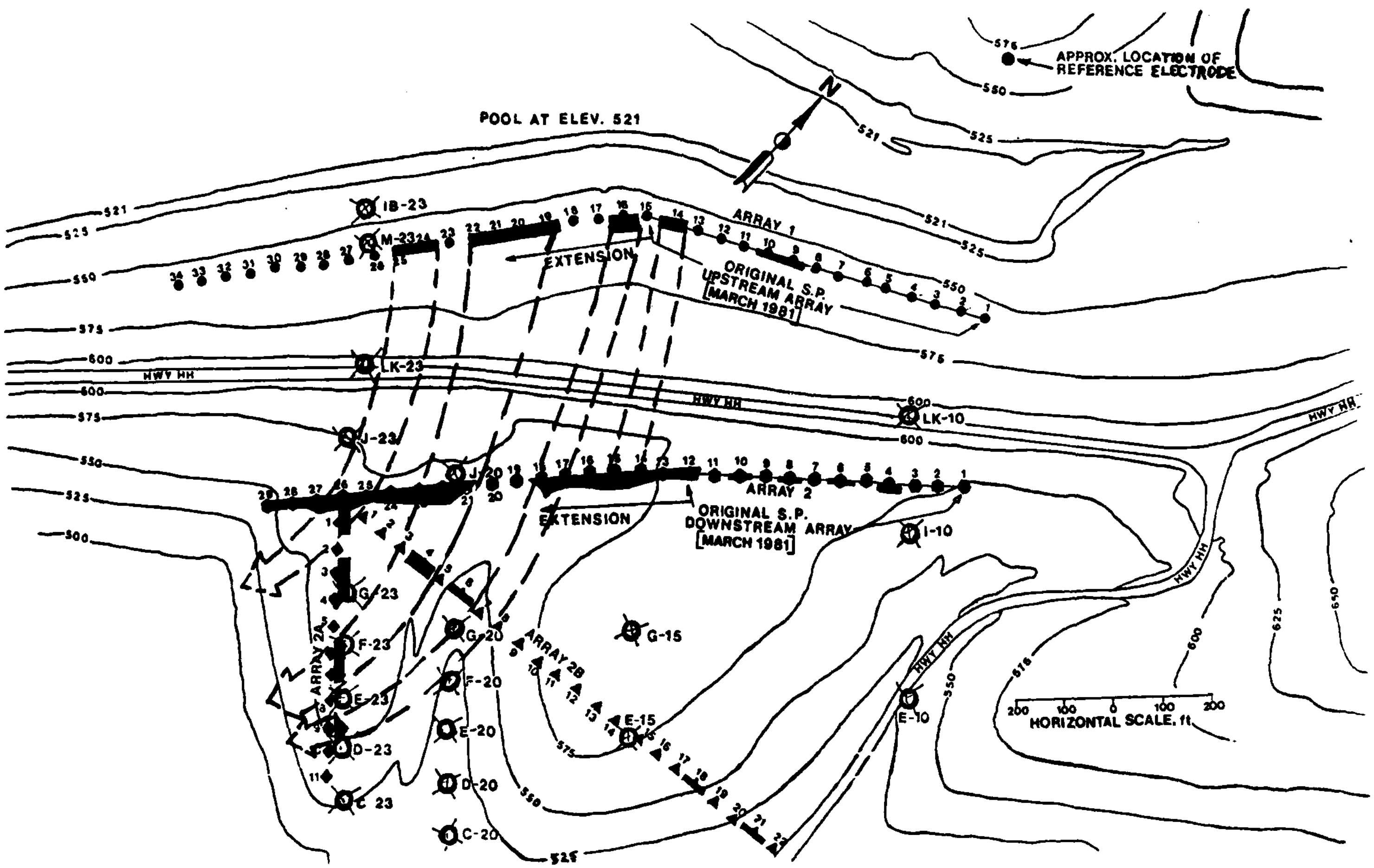

Figure A4. Possible seepage paths based on SP results.

END

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